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Dissociation and Recombination Effects on the Performance of Pulse Detonation Engines

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September 2003

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DISSOCIATION AND RECOMBINATION EFFECTS ON THE PERFORMANCE OF PULSE DETONATION ENGINES

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Abstract

This paper summarizes major theoretical results for pulse detonation engine performance taking into account real gas chemistry, as well as significant performance differences resulting from the presence of ram and compression heating.

An unsteady CFD analysis, as well as a thermodynamic cycle analysis was conducted in order to determine the actual and the ideal performance for an air- breathing pulse detonation engine (PDE) using either a hydrogen-air or ethylene-air mixture over a flight Mach number range from 0 to 4. The results clearly elucidate the competitive regime of PDE application relative to ramjets and gas turbines.

Introduction

Many excellent reviews of PDE's have been published[9,10] and it is not our intent to review that literature. Instead, we will adopt a somewhat narrow point of view and limit this discussion to our previous work on *real gas chemistry and heating effects due to compression.*

a. Sensible Heat Release
In our previous work[1] we have shown the importance of real gas chemistry in detonation propulsion devices. A significant decrease in the sensible heat available for thrust was found to occur in PDE propulsion systems due to high temperature dissociation. A subsequent analysis[2] was carried out to compare the specific thrust, fuel consumption and impulse for a ramjet, a turbine engine (with variable amounts of mechanical compression) and a pulse detonation engine, as a function of flight Mach number. In that study, it was found that a PDE could provide comparable performance with a ramjet over a range of Mach numbers. Relative to the turbojet, however, the PDE was competitive only when the turbojet's mechanical compression was very low, of the order of 4.

b. Species Recombination
Subsequent to the studies mentioned above, CFD analyses were performed for an opened ended detonation tube[3]. The computation, which included finite rate chemistry effects, showed that some recombination occurred in the burning gases behind the detonation wave. The recombination served to decrease the amount of sensible heat loss that occurs during the detonation process.

c. Performance Calculations
In a later paper[4], the sensible heat release obtained from a finite rate CFD analysis was used to compute the impulse in an open- ended detonation tube. The same heat release was then used in a thermodynamic cycle code to calculate impulse. The difference in the two impulse values was assumed to represent the additional maximum potential performance attainable in a PDE. Those results were compared with experimental impulse data, which indicated a potential performance gain in specific impulse of 200 to 300 seconds.

Most recently, we have computed the performance of a hydrocarbon-air PDE over a wide Mach number range to demonstrate the potential usage in a combined cycle accelerator[5].

Approach for the Comparative Analyses of Cycle Performance

a. Fundamental Considerations
The advantage of the pulse detonation engine (PDE) cycle over the Brayton cycle has usually been attributed to the higher thermodynamic efficiency of the PDE. This cycle advantage is normally depicted as a plot of thermal efficiency versus relative inlet temperature ratio, where the atmospheric temperature is used as the reference. The typical plot, shown in figure 1, assumes that a comparison of the different cycles is performed at a constant value of the temperature ratio, regardless of the type of cycle and the flight conditions. In addition, the heat release for all of the engine cycles is assumed

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to be equal. The usual result from figure 1, therefore, would show that at a temperature ratio of 2, the cycle efficiency for the PDE is 0.63, while that for a Brayton cycle is only 0.5. There are two fallacies associated with this type of comparison; namely (I.) the temperature ratio, T_3/T_0 (where T_0 is the atmospheric temperature), entering the combustor of a pulse detonation engine or a ramjet is lower than that of the gas turbine, and (II.) the available heat released in the detonation cycle is lower than that in a Brayton (either gas turbine or ramjet) cycle. In this paper, we shall examine both of these issues in some detail, in order to establish an improved comparative basis for the propulsion performance of each of the cycles. Some typical flight conditions will be assumed in order to demonstrate the effects mentioned above.

b. Inlet/Compressor Temperature Rise

In regards to issue (I.), the PDE and the ramjet utilize only *ram* compression and heating to increase the inlet temperature ratio, T_2/T_0, where T_0 is the atmospheric or reference temperature and T_2 is the temperature of the air exiting the inlet and diffuser section of the engine. In the case of the gas turbine, the ram compression is further boosted by the *mechanical* compressor (and fan) to a temperature T_3 that is higher than that in the PDE or ramjet. In order to compare the relative performances, it is necessary, therefore, to use the value of the temperature, T_2, entering the PDE detonation chamber (or into the ramjet combustion chamber) as well as the higher temperature, T_3 entering the gas turbine combustion chamber. ***The effect of using these temperatures is to shift the comparison point between the PDE (and the ramjet) and the gas turbine cycles to different locations on the abscissa of figure 1.***

Therefore, the cycle comparison in figure 1 must be modified so that the PDE efficiency comparison is now made with the corrected (or higher temperature ratio) gas turbine efficiency. The value of the higher temperature ratio for the turbine depends on the amounts of mechanical compression. For example, if the specific heat ratio is 1.4 and the flight speed is Mach 1, then the ram temperature ratio value is 1.2. If the mechanical compression ratio is 2, the resulting temperature ratio is 1.49. This means that if the comparison point for cycle efficiency was at a temperature ratio of 1.2 for the PDE (upper square symbol in figure 1), then the temperature ratio for the gas turbine should be at 1.49 (lower square symbol in figure 1, rather than the lower triangular symbol).

The paper presents results for the propulsion performance parameters, i.e., specific thrust, impulse and specific fuel consumption as a function of flight Mach numbers, accounting for the correct inlet temperatures as well as real gas effects, which are described in the next section.

c. Sensible Heat Availability

In regards to issue (II.), it has been shown that the ***higher temperatures associated with the detonation process creates a greater amount of dissociated species and lower sensible heat release than does the deflagration process in a ramjet or gas turbine engine***. Figures. 2 and 3 show previous results considering only dissociation losses.

Use of a time accurate CFD code including finite rate chemistry has been used to determine the combined dissociation and recombination occurring in an open-ended PDE tube. The resulting effect on the amount of sensible heat available for creating thrust is significant and, in fact, causes the specific thrust, impulse and fuel consumption values for the PDE to become inferior to the gas turbine at some conditions, as shown in figure 2.

d. Ethylene-air Computations

Our goal is to determine the real gas effects on performance with a typical hydrocarbon-air mixture, over a Mach number range with the additional requirement of proper accounting for ram and compression heating effects.

In order to determine the sensible heat available for the PDE, an unsteady CFD method[6] was used in ref. 7 was used to determine the value of the sensible heat release including both dissociation and recombination. The resulting value was then used in the thermodynamic cycle analysis[8] to determine the specific thrust, fuel consumption and impulse for a range of Mach numbers.

It is noted that the short mechanism of ref. 11 was used in order to enable reasonable computational time.

e. Validation of Analysis Methods

The impulse results for the thermo cycle analysis and the CFD results for hydrogen-air mixtures are compared with experimental data in figure 4. The agreement provides us with some measure of confidence in our approach. The cycle results are considered to be the ideal whereas the lower impulse CFD values reflect the actual conditions occurring in the experimental tests.

Results

a. Specific Thrust

The results are shown in figure 5 for stoichiometric ethylene-air for Mach numbers from 0 to 5, accounting for the correct inlet/compressor temperatures and for dissociation and recombination. It is seen that the PDE performance exceeds that of a ramjet out to a value of about Mach 3.5, and is equivalent to that of a turbojet at the same point.

b. Specific Fuel Consumption

The specific fuel consumption of the PDE is less than the ramjet out to about Mach 2.5, and always slightly greater than the gas turbine, see figure 6.

The impulse of the PDE exceeds the ramjet out to Mach 3.5 and is then equivalent. In the case of the gas turbine, the impulse is greater out to Mach 2.5 and is then equivalent thereafter.

c. Impulse

It is noted that the value of the impulse from our thermo cycle analysis calculation is 2019 seconds at a temperature ratio of 1, and the maximum point from our unsteady CFD is 1962 seconds. The difference in the cycle value and the CFD represents a potential performance improvement.

d. Significance of Results

The overall significance of these results is that PDE's have a flight range over which they can be competitive from a theoretical propulsion viewpoint as shown above; namely as an alternative to ramjets with significant improvement over the entire Mach number range.

Two common fallacies in the comparison of propulsion power cycles have been discussed to some depth in this paper and the proper procedures for making relative comparisons were described.

The results described in this paper clearly establish two items having major technical significance on cycle performance:

(1) the critical impact of real gas chemistry on the performance of PDE's and

(2) the need to differentiate between the PDE and Brayton cycles in establishing the correct initial temperature condition which accounts for both ram and compression heating.

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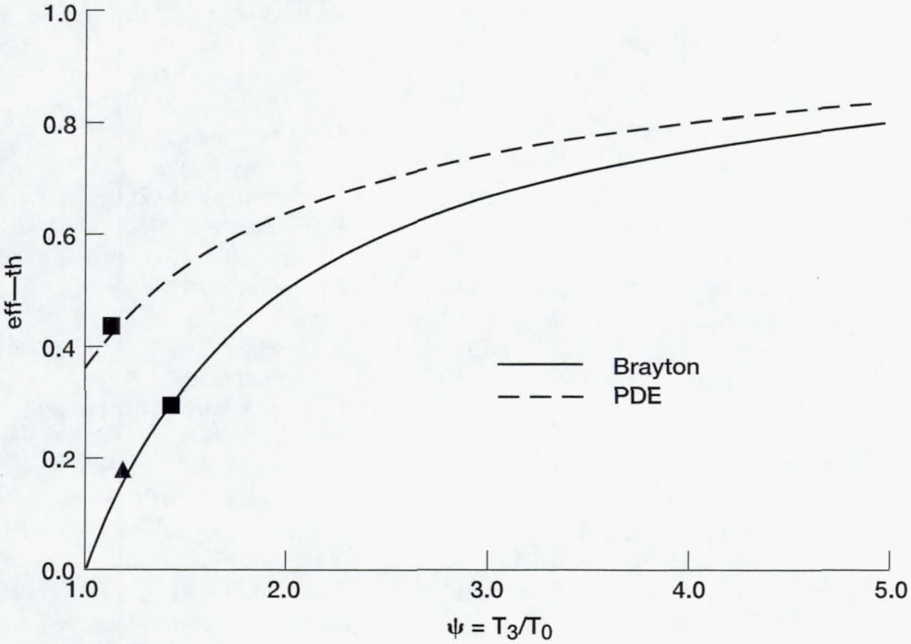

Figure 1.—Thermal efficiency for the PDE and Brayton Cycles, stoichiometric propane-air. Significance of symbols discussed in text.

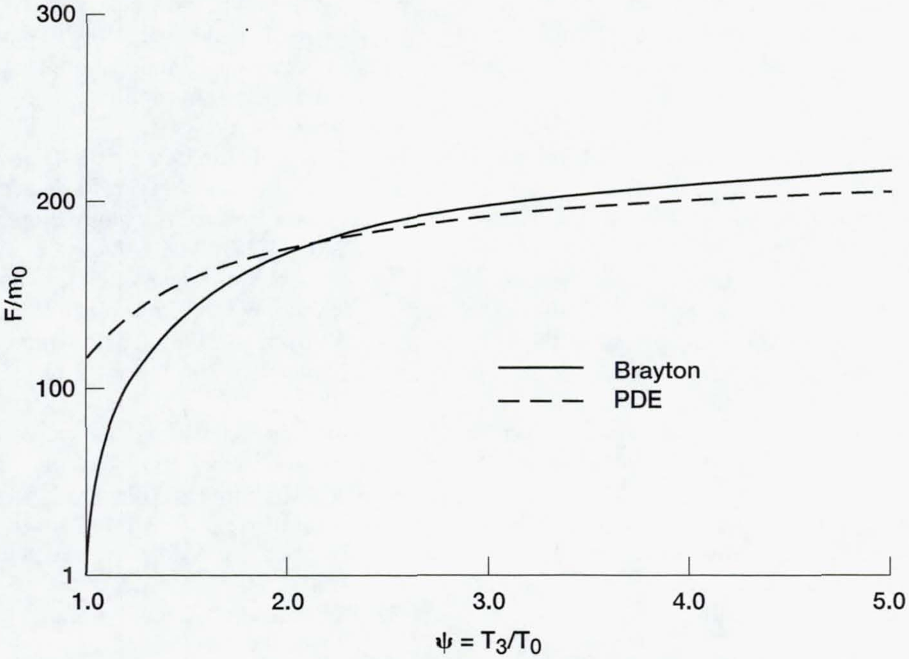

Figure 2.—Specific thrust for the PDE and Brayton cycles, stoichiomettric propane-air.

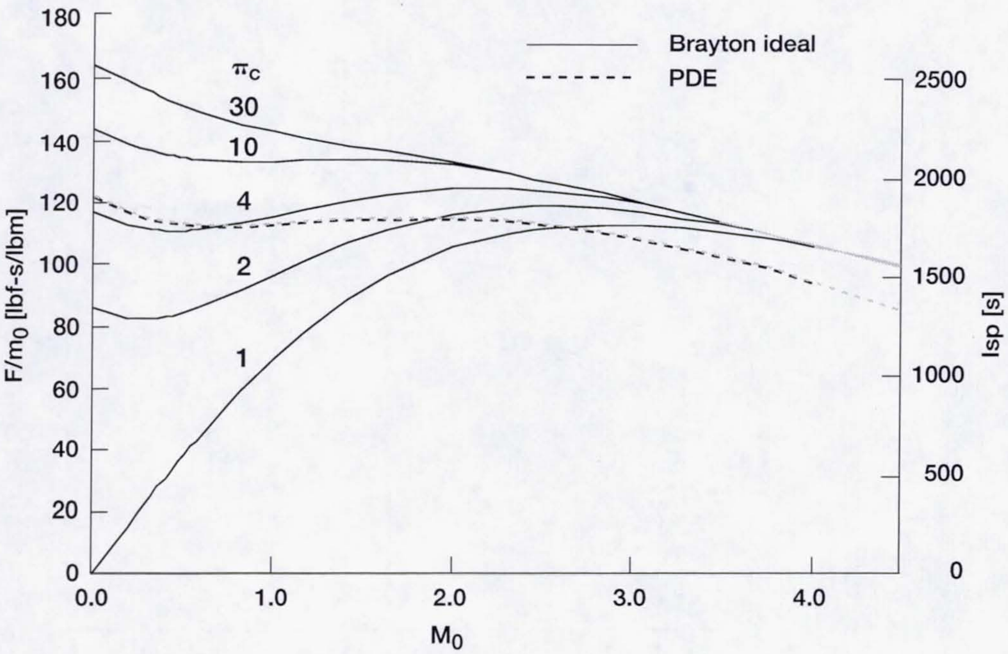

Figure 3.—Specific thrust versus Mach number for Brayton and PDE cycles, stoichiometric propane-air, numbers on plot represent the Brayton mechanical compression ratio, dissociation losses only, flight at 33K feet.

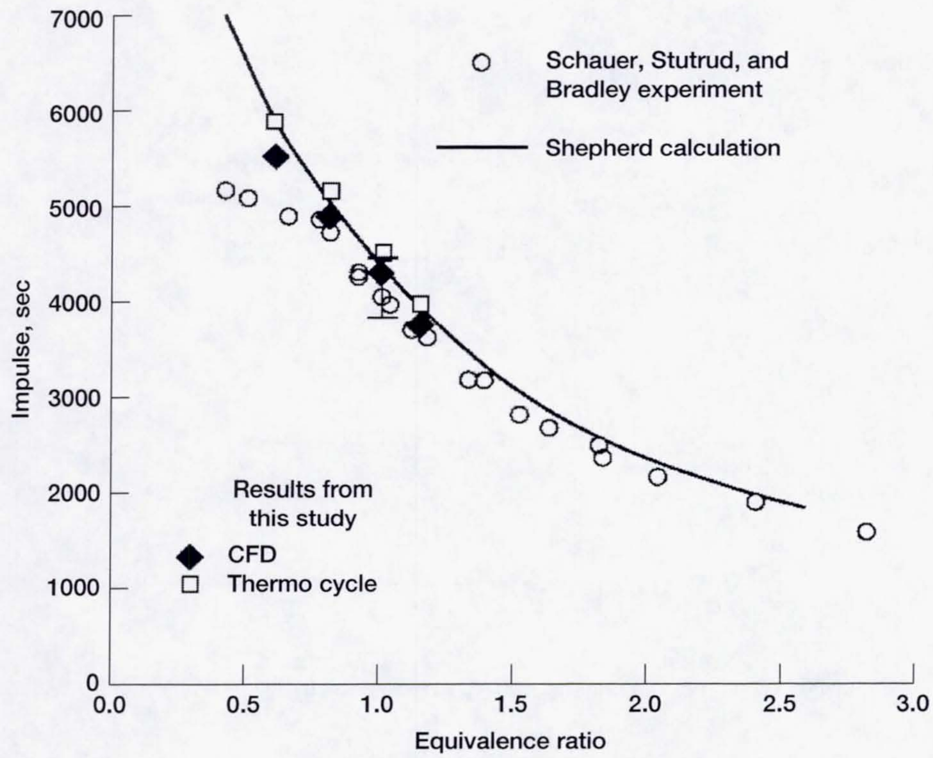

Figure 4.—Comparison of analyses with Wright Labs data, hydrogen-air.

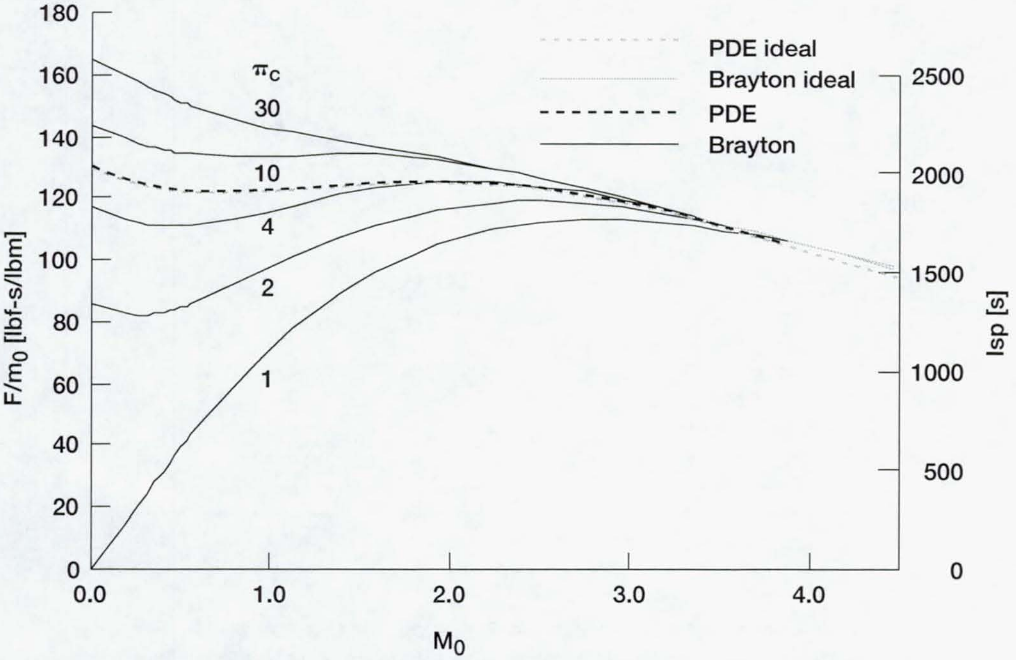

Figure 5.—Specific thrust versus Mach number including real gas effects of dissociation and recombination, stoichiometric ethylene-air, flight at 33K feet.

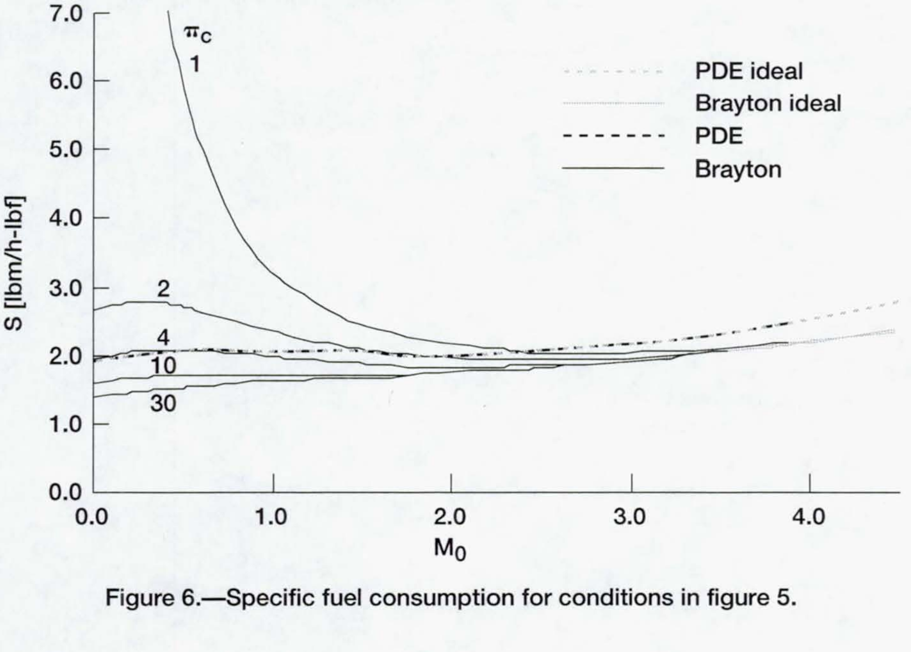

Figure 6.—Specific fuel consumption for conditions in figure 5.

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13. ABSTRACT *(Maximum 200 words)*

This paper summarizes major theoretical results for pulse detonation engine performance taking into account real gas chemistry, as well as significant performance differences resulting from the presence of ram and compression heating. An unsteady CFD analysis, as well as a thermodynamic cycle analysis, was conducted in order to determine the actual and the ideal performance for an air-breathing pulse detonation engine (PDE) using either a hydrogen-air or ethylene-air mixture over a flight Mach number range from 0 to 4. The results clearly elucidate the competitive regime of PDE application relative to ramjets and gas turbines.

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